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Micro parts processing using laser cutting and ultra-short-pulse laser peen forming

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Abstract

Laser peen forming is a sheet metal forming process using laser induced shock waves. The laser peen forming with an ultra-short-pulse laser is a kind of non-thermal and die-less forming process, and is favorable for micro forming. The authors applied the laser peen forming to the bending of pure titanium thin sheet with a picosecond laser and a femtosecond laser. The changes of bending properties with atmosphere and pulse duration were investigated. The femtosecond laser irradiation in air showed the best bending efficiency. The femtosecond laser is applicable to laser cutting, also. Some thin sheets were cut into complicated shapes and bent by laser peen forming with femtosecond laser. The combined process allowed the production of various complicated small parts.

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1. Introduction

Recent improvement of laser-oscillating technology allowed the appearance of ultra-short-pulse laser, which has a pulse duration of picosecond (10^{-12} s) or femtosecond (10^{-15} s) order. They are called picosecond laser (ps laser) and femtosecond laser (fs laser) respectively. Such very short pulses show unusual processing behaviors. A laser is usually recognized as a heat source. However, the shorter pulse laser causes less temperature rise to a target.

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Especially, the fs and ps laser processes are often called non-thermal processes. Therefore, they are unfavorable for laser forming, which is a sheet metal forming based on the thermal stress induced by laser irradiation. However, an ultra-short-pulse laser is useful for metal forming. It is because a focused pulse laser can induce shock waves at an irradiated target surface. The shock waves can deform a metal target plastically under some irradiation conditions.

Some applications of the laser induced shock waves to metal forming have been proposed with nanosecond (10^{-9} s) pulse laser (ns laser). Vollertsen and Sakkietibutra (2010) have proposed a sheet stretch forming using shock waves. It has been called laser shock forming. Another application to sheet metal forming is a laser peen forming. It uses similar forming principle to a peen forming, which is an application of shot peening to sheet metal forming, but the impacts of shots are replaced by the laser induced shock waves. O'Hara (2002) has reported aircraft skin panel production by the ns laser peen forming. A fs laser, also, is usable for laser peen forming. Sagisaka et al. (2010) have applied the fs laser peen forming to a thin-sheet-metal bending. The non-thermal processing property of the fs laser is favorable for the production of micro parts, which hate thermal influences.

In the present paper, the laser peen forming with fs laser and ps laser were applied to the bending of pure titanium thin sheet, in order to find the best irradiation conditions for micro parts forming. The influences of atmosphere and pulse duration on forming properties were investigated. In addition, the authors attempted to propose a new micro process using the ultra-short-pulse laser. The laser cutting is useful for producing various shaped small sheets. The bending after laser cutting will realize various complicated micro parts, which are effective in miniaturization of medical instruments and electronic equipment. Some trial productions of small parts were performed by the combined process of laser cutting and laser peen forming.

2. Principle of laser peen forming

When a high intensity short laser pulse is focused on a sheet metal, the irradiated top surface is ionized and removed instantaneously. This phenomenon is called laser ablation. A high-pressure plasma is generated by the ionization. Although the plasma expands rapidly, the inertial force of atmosphere confines the expansion. As a result, the irradiated surface is subjected to a momentary high pressure and a shock wave propagates into the sheet metal. When the sheet is irradiated in water, the large inertial force of water confines plasma expansion strongly and makes pressure larger. This effect has been confirmed by a lot of researchers, such as Fox (1974), with ns laser. The irradiated surface is pressed and elongated to the lateral direction as shown in Fig. 1(a). The laser peen forming is achieved by scanning the laser and accumulating such deformations. The sheet is curved, as the irradiated surface is convex (Fig. 1(b)). The direction of curve is opposite to that of usual laser forming.

The authors applied this method to thin-sheet-metal bending. Sagisaka et al. (2012) have shown that the fs laser is applicable to the bending of stainless steel and other materials. However, the fs laser has serious troubles in the cost of oscillating system. The authors adopted a ps laser, which is more advantageous in cost, as a substitute for the fs laser. Griffiths et al. (2012) has reported the laser forming with high-frequency ps laser of 500 kHz. When the pulse frequency is high, even the ps laser can cause thermal effects. However, when the pulse frequency is low and the pulse energy is high, a ps laser can induce enough shock waves for plastic deformation.

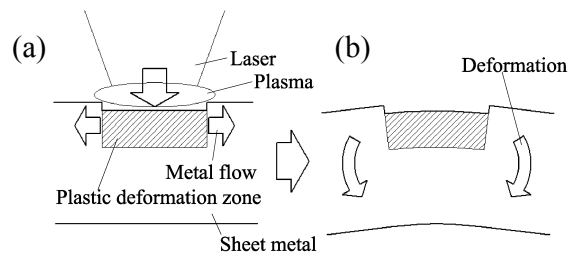


Fig. 1. Principle of laser peen forming: (a) Irradiation; (b) Deformation.

3. Comparison of forming properties

The changes of forming properties with pulse duration were investigated. In order to clarify the influence of atmosphere, the irradiations were performed in air and in water.

3.1. Experimental set-up

The specifications of used ps and fs laser are shown in Table 1. The summary of laser processing equipment is shown in Fig. 2. The pulse energy E was controlled by a neutral density filter. The laser beam was focused by a 35 mm focal lens. In case of irradiation in water, a workpiece was mounted in a transparent container filled with water.

An outline of experimental procedure is shown in Fig. 3. A pure titanium (JIS Grade I, 240HV) sheet of 50 μm thickness was adopted as the workpiece. It was cut into strips of 5 mm \times 30 mm by laser cutting with the fs laser. The workpiece was mounted on the 3-axis motorized stage with a clamp. The laser scanned over the hatched area of the workpiece. The scanning was performed by moving the motorized stage. The scanning speed was 5 mm/s. The scanning path is shown in Fig. 3(a). The lateral scanning pitch p_1 was decided by the pulse frequency. It was 5 μm and 4 μm for the fs and ps laser, respectively. The longitudinal scanning pitch p_2 was 100 μm . The spot diameter d was controlled by defocusing the workpiece axial to the direction of the laser beam. The focal point was defined as the original point of the defocus distance z . When the workpiece was shifted toward the beam source, z was defined as positive. The minimum d was about 40 μm . The bending angle θ was measured after scanning.

3.2. Experimental results

The changes of bending angles θ with defocus distance z are compared in Fig. 4. The θ obtained by fs laser irradiations were influenced by the atmosphere remarkably. Those in air were very large and sensitive to the z . The largest θ was obtained around the focal point. When pure aluminum workpieces have been irradiated in water, the largest θ has been obtained at the z of 0.3 to 0.6 mm (Sagisaka, 2010). However, pure titanium workpieces irradiated in water showed very small θ of almost zero. The plasma confining effect of the water was not observed. The focused fs laser pulse is easy to be absorbed by the water, due to its high peak power. The pulses, which were absorbed and weakened before arriving at the target, could not induce strong shock waves at the target surface. Although the shock waves were enough to deform the pure aluminum, they were insufficient to deform the pure titanium. The fs pulses were absorbed by the air, also. However, its influence was not observed.

Table 1. Specifications of ultra-short-pulse lasers.

Laser	Wave length	Pulse duration	Pulse frequency	Pulse energy
ps	1064 nm	10 ps	1.26 kHz	$\leq 200 \mu\text{J}$
fs	800 nm	80 fs	1 kHz	$\leq 400 \mu\text{J}$

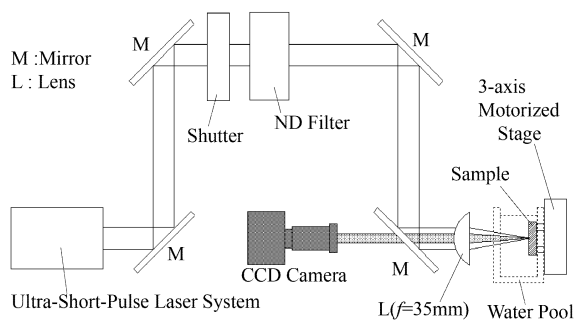


Fig. 2. Schematic diagram of experimental equipment.

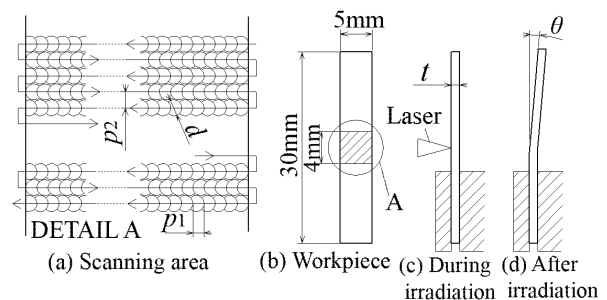


Fig. 3. Schematic diagram of experimental set-up.

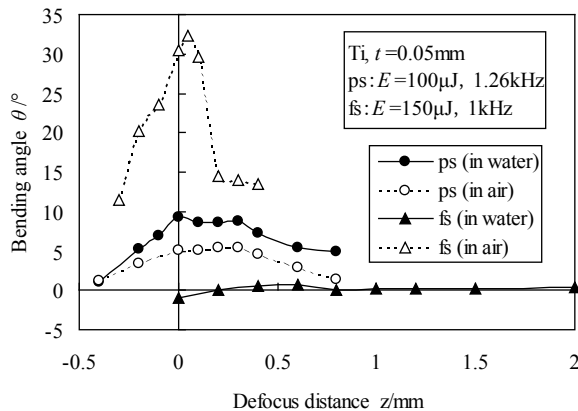


Fig. 4. Change of bending angles with defocus distance.

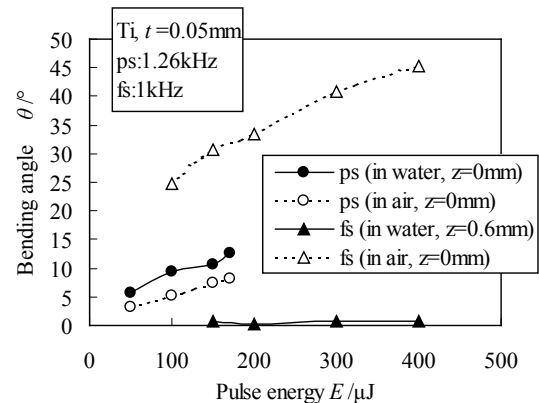


Fig. 5. Change of bending angles with pulse energy.

In contrast, the ps laser showed the similar changes of θ regardless of atmospheres. The ps laser pulse has much lower peak power than the fs laser pulse. It means that the absorption by the water is much smaller. Even the weakened ps laser pulses could induce enough shock waves. θ obtained by the irradiations in water was larger than those in air. The plasma confining effect of the water would be stronger than the unfavorable effect of the absorption. θ was insensitive to z . This will be favorable for the bending accuracy. However, the bending efficiency was inferior to the fs laser irradiation in air.

The changes of θ with pulse energy E are compared in Fig. 5. The experiments were performed at z , around which the largest θ was obtained in Fig. 4. Although θ usually increased with the E , those of the fs laser irradiation in water were around zero. The large E of fs laser did not contribute to increasing the shock waves in water. Most of the increased energy would be absorbed by the water. The best bending efficiency was achieved by the fs laser irradiation in air. It is favorable for obtaining small radius of curvature, which is necessary for micro parts.

4. Combined process of laser cutting and laser peen forming

A weak point of the laser peen forming is its long processing time required for the scanning. A micro part is one of favorable objects for the process, because its small scanning area reduces processing time. The fs laser, which showed the best bending efficiency, is applicable to a laser cutting. The laser cutting is one of favorable methods for preparing a complicate shaped small sheet. The bending of laser cut sheet will allow a new complicated micro part. The authors proposed a new combined process of cutting and bending with the fs laser.

4.1. Application of bending to one direction

A curling shape was tried at first. A pure titanium sheet of 50 μm thickness was cut into comb shape, as shown in Fig. 6(a). The scanning was performed several times until cutting off. The scanning speed was 1 mm/s, which was slower than that of bending, because fast scanning made the quality of cut surface worse. However, slow scanning and large pulse energy E promote the thermal storage at the irradiated portion and spoil the non-thermal property of the fs laser. When the E was too large and the tooth width w was small, the teeth were warped during the cutting, as the irradiated side is concave, due to the thermal effect. The warping should be avoided, because it made the defocus distance unstable in the following bending process. The bending deformation with the fs laser was sensitive to the defocus distance, as shown in Fig. 4. As a conclusion of some experiments, the maximum E , which could restrain the warping small enough, was estimated as 150 μJ .

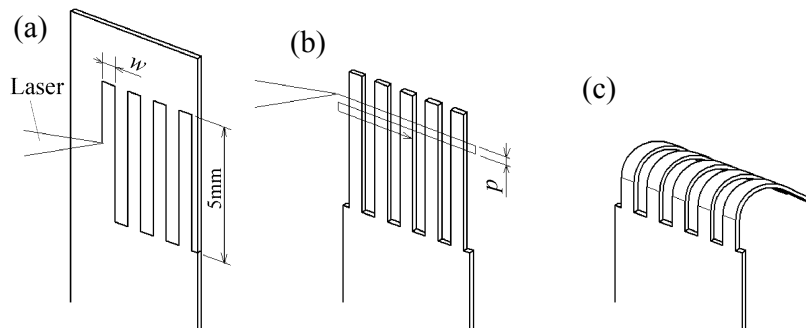


Fig. 6. Combined process for one direction bending : (a) Cutting; (b) Bending; (c) After processing.

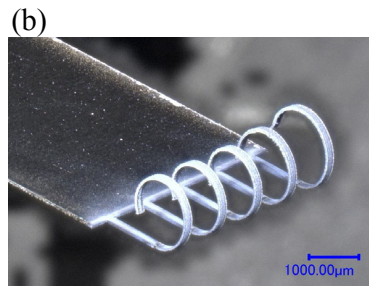
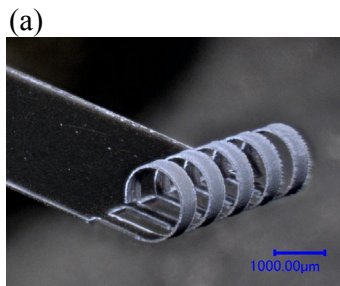


Fig. 7. Examples of curling shape : (a) $w=0.5\text{mm}$; (b) $w=0.2\text{mm}$.

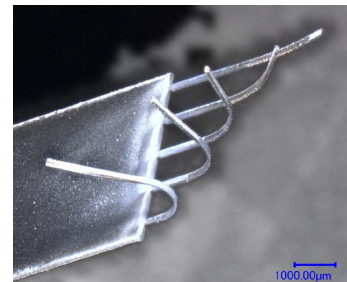


Fig. 8. Bending in various curvatures ($w=0.2\text{mm}$).

After the cutting, the comb teeth were scanned the surface and bent, as shown in Fig. 6 (b) (c). The scanning speed was 5 mm/s. The E was 400 μJ . The longitudinal scanning pitch p was 10 μm . The bent workpieces with various w are shown in Fig. 7. The minimum radii of curvature were 0.7 and 0.73 mm for Fig. 7(a) and (b), respectively. The curling shapes were possible to form. However, when the w was small, the radii of curvature were not constant. The restraint of warping might not be perfect. Fig. 8 shows a comb shaped sheet, which was bent tooth by tooth with various scanning pitch p of 10, 15, 20, 40 and 100 μm . Various curvatures were possible by changing the scanning program.

4.2. Application of bending to both directions

A workpiece was cut into the shape of three-pronged fork, as shown in Fig. 9. After the cutting, it was bent into S-shape by the irradiations on the front and backsides. The irradiations on the backside were performed after

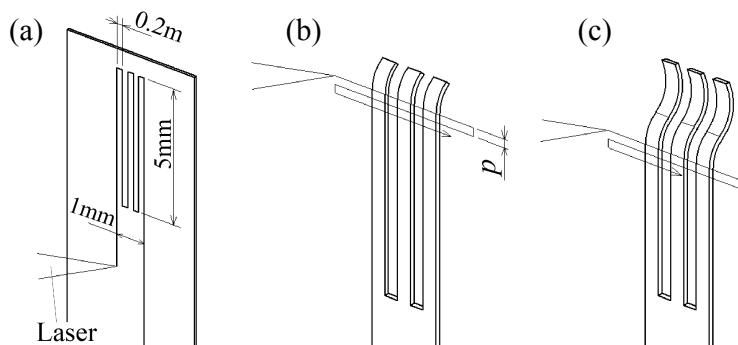


Fig. 9. Combined process for both direction bending: (a) Cutting; (b) Irradiation on front side; (c) Reversing and irradiation on backside.

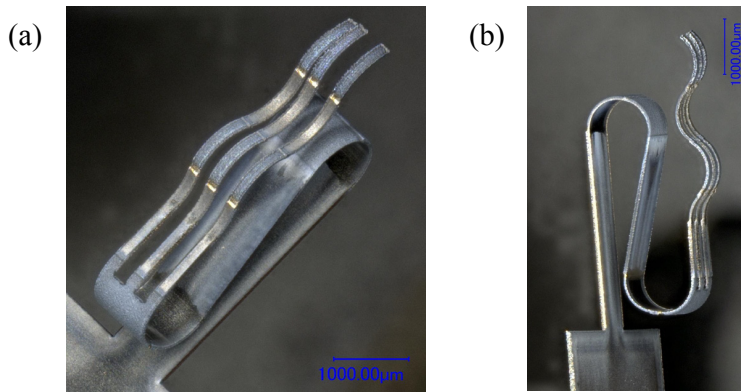


Fig. 10. Example of S-bending: (a) Front view; (b) Side view.

reversing the workpiece (Fig. 9 (c)). The reversing and scanning were repeated several times. The irradiation conditions were same as those of curling shape. The p was 10 μm .

An example of S-bending is shown in Fig. 10. The average radius of curvature was 0.62 mm. It showed that the combined process of cutting and bending was applicable to the small parts production. However, the intervals between the teeth ends were not constant. It was caused by the unfavorable in-plane distortion during the bending. In addition, the curvatures at the teeth were often scattered. The accuracy is the next theme for the process.

5. Conclusions

Some pure titanium thin sheets were bent by the fs and ps laser peen forming. The deformation behaviors were differed by the pulse duration and the atmosphere. The ps laser irradiations in water showed better bending efficiency than those in air. In contrast, the fs laser irradiations in water generated little deformation, due to the absorption by the water. However, those in air showed superior efficiency, and were best for micro parts forming. The authors proposed a new combined process of laser cutting and laser peen forming with the fs laser. Some trials were performed, and the formed workpieces showed the potential of the process for micro parts production.

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